

# Investigating the Spectral Anomaly with Different Reactor Antineutrino Experiments

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The spectral shape of reactor antineutrinos measured in recent experiments shows anomalies in the neutrino flux predictions. New precision measurements of the reactor neutrino spectra as well as more complete input in nuclear data bases are needed to resolve the observed discrepancies between flux models and experimental results. We combine experiments at reactors which are highly enriched in  $^{235}\text{U}$  with commercial reactors with typically lower enrichment to gain new insights into the origin of the anomalous neutrino spectrum. As an example, we discuss the option of a direct comparison of the measured shape in the currently running Double Chooz near detector and the upcoming Stereo experiment.

Keywords: antineutrino; neutrino; reactor spectrum; reactor anomaly; nuclear reactor

Intense research in the past few years has brought new insights in the antineutrino spectra emitted by nuclear reactors. Direct measurements of the antineutrino spectra as well as their improved predictions were a product of the search for the non-zero neutrino mixing angle  $\theta_{13}$  at the km-baseline reactor experiments Double Chooz [1], Daya Bay [2] and RENO [3]. Although the experiments were successful at determining the  $\theta_{13}$  parameter, the comparison of the measured spectra of km and short-baseline experiments to the most up-to-date predictions showed significant discrepancies both in absolute flux and spectral shape. The inconsistency in total flux has a statistical significance of  $2.7\sigma$  and is known as the reactor antineutrino anomaly [4]. The energy shape distortion manifests itself as a shoulder in the detected spectra at  $E_\nu \sim 6\text{ MeV}$  antineutrino energy [5].

To date it is unknown if these differences indicate unaccounted physics in the propagation and detection of neutrinos. On the other hand, they could be introduced by the computational methods, theoretical assumptions or incomplete data inputs used to yield the predicted spectra. Furthermore, the two anomalies are in general treated as independent observations possibly caused by independent effects.

Upcoming experiments will test if the discovered overall deficit in antineutrino rate is linked to neutrino flavour oscillations into a light sterile state [6]. Being a possible explanation for the flux puzzle, this quantum mechanical phenomenon, however, does not explain the shoulder in the antineutrino spectra. This article will discuss the potential of current and future reactor neutrino experiments to resolve the spectral shape distortion by combining spectra from different reactor types.

Nuclear reactors represent intense and extremely pure sources of electron antineutrinos with energies extending up to about 10 MeV. Commercial power reactors are fueled with Low Enriched Uranium (LEU). Only a few percent of the fissile  $^{235}\text{U}$  is contained in the initial reactor fuel. During operation, more than 99 % of

the emitted antineutrino flux is created by  $\beta$ -decays of the fission products of  $^{235}\text{U}$ ,  $^{238}\text{U}$ ,  $^{239}\text{Pu}$  and  $^{241}\text{Pu}$ . The new generation of experiments at km-baselines triggered a re-evaluation of the expected antineutrino spectra of nuclear reactors. The former measurements at  $<100\text{ m}$  distances from the reactor cores as well as the pioneering km-baseline detectors CHOOZ [7] and Palo Verde [8] relied on the conversion spectra of Ref. [9–12]. Input of the conversion scheme is based on high-precision electron spectrum measurements at the BILL spectrometer at ILL [13]. Each of three actinides  $^{235}\text{U}$ ,  $^{239}\text{Pu}$  and  $^{241}\text{Pu}$  were exposed to thermal neutrons to undergo fission and create the beta-unstable fission fragments.

In 2011 Mueller et al. [14] as well as Huber [15] published new antineutrino reference spectra computed from the same electron spectrum measurements as Ref. [10, 12], but with revised conversion technique. Both found a 4 % increase in the reactor flux compared to the previous prediction, which had been applied as standard for more than 20 years. A reanalysis was performed using the antineutrino flux measurements at 100 m baseline and less. Together with an updated neutrino interaction cross section the computation resulted in an observed-to-predicted ratio of  $0.935 \pm 0.024$  [16], which is the previously mentioned reactor anomaly. The electron spectrum of  $^{238}\text{U}$  was first measured by Haag et al. [17] by means of fast neutron bombardment of  $^{238}\text{U}$ -foils. Up to this point the  $^{238}\text{U}$  antineutrino spectrum was computed using nuclear databases as input. For each actinide  $k$  the antineutrino spectrum  $S_k(E_\nu)$ , assuming production of the fission products at equilibrium, is given by

$$S_k(E_\nu) = \sum_i Y_i^k \sum_b \text{BR}_b^i \cdot S_b^i(E_\nu, E_{0,b}^i, Z_b, A_b). \quad (1)$$

Here,  $Y_i^k$  is the cumulative fission yield of the  $i$ th fission isotope.  $\text{BR}_b^i$  denotes the branching ratio of a particular beta decay  $b$  of the  $i$ th fission product, whereas the antineutrino spectrum of this decay is  $S_b^i$ . The latter depends on the endpoint energy  $E_{0,i}$  as well as the

nuclear charge  $Z_i$  and the atomic number  $A_i$  of the daughter nucleus.

At present the commonly used antineutrino reference spectra are from the Huber conversion plus  $^{238}\text{U}$  from either the Mueller computation or the conversion of Haag's measurement. The spectra are then often referred to as based on Huber-Mueller or Huber-Haag, respectively.

Several theoretical articles discussed the influence of first forbidden decays on the prediction of antineutrino spectra [18, 19]. The resulting energy dependence of the nuclear matrix element translates as a correction into a broadening or shifting of the spectral shape and thus the average neutrino energy. As the  $\bar{\nu}_e$  detection via inverse beta decay (IBD) has a detection threshold, the predicted event rate changes with the theoretical assumptions for the forbidden decays. The size of the systematic uncertainty of current reactor predictions is however still under discussion and necessitates dedicated studies involving realistic assumptions.

Improvements on the performance of the km-baseline experiments such as energy resolution, energy scale uncertainty and accumulation of higher statistics allowed to accomplish precision measurements of the reactor antineutrino spectra and surprisingly a shoulder in the energy spectrum at  $E_\nu \sim 6\text{ MeV}$ . When the ratio of measured and predicted spectrum is built, this shoulder becomes a “bump” in this energy region. The excess of events measured in the shoulder region of 5-7 MeV was found to be significant at  $3\sigma$  and correlated to the thermal power of the reactors [5]. Currently it is considered to be a common feature in all high-precision measurements of the antineutrino energy spectrum at nuclear reactors [20, 21], however with different magnitude of the effect. As a consequence, there is widespread expectation that the spectral distortion is linked to inaccurate antineutrino reference spectra. This assumption is supported by thorough studies, as in Ref. [5], which question explanations of the shoulder being due to unaccounted backgrounds or detector response. However, owing to limited calibration data in the energy region of interest, a common bias in the non-linearity modelling, e.g. from approximations and simplifications in the quenching model of Birks [22, 23], should not be fully excluded yet. Double Chooz, Daya Bay and RENO rely not only on a similar detector design but also the same IBD detection technique, all using Gd doped liquid scintillators. Therefore independent confirmation of the spectral distortion with a different detector technology would be desirable.

Using the summation method of Eq. (1), Dwyer and Langford [24] obtained a similar structure in both their predicted electron as well as antineutrino spectra. Furthermore, they pointed out that only few isotopes appear to contribute to the antineutrino spectrum

above  $\sim 5\text{ MeV}$ , predominantly  $^{96}\text{Y}$  and  $^{92}\text{Rb}$  (see also Ref. [25]). The authors of [25] and Ref. [26] emphasized the importance of branching ratio measurements free of the pandemonium effect [27], which are called TAGS (Total Absorption Gamma-ray Spectroscopy) data. In particular the case of  $^{92}\text{Rb}$  is discussed, for which the inclusion of the TAGS measurement significantly changes the antineutrino spectrum at high energies. Dwyer and Langford did not account for the TAGS data, hence the shoulder in their spectrum is very likely overestimated. Moreover, the uncertainties on summation spectra, are known to be sizable [4], if not even by far underestimated as suggested by Ref. [28], where the authors use different fission yield databases to evaluate reactor spectra based on the summation method. When the ratio to the Huber-Mueller prediction is built, a bump in the energy region of about 5-7 MeV emerges or vanishes, depending on the database used. In comparison to the Huber-Haag prediction the bump is present for both databases. The discrepancies in the fission yields of different databases can hence create structures in the spectra, which are not necessarily covered by the systematic uncertainties quoted. Recent studies have shown that biases in the fission yield databases might cause the spectral structure described in [24] and [28], which implies that the databases need to be revised [29].

In addition, Hayes et al. [28] find hints for  $^{238}\text{U}$  being one of the actinides that might contribute significantly to the shoulder. The authors identify a possible correlation of the  $^{238}\text{U}$  content in the fuel of Double Chooz, Daya Bay and RENO and the relative overshoot of the spectrum in the bump region.

In general summation spectrum calculations suffer from a lack of experimental data, which is replaced by theoretical assumptions, introducing sizable uncertainties. Even with the inclusion of theoretical inputs, we can see in Ref. [28] that the normalization of the BILL measurements is not reached. Therefore experimental data from different reactor types could bring valuable insights into the nature of the reactor shape distortion bypassing the use of summation spectra and accordingly their large uncertainties.

There are three experiments currently measuring the antineutrino flux emitted at nuclear reactors and which are suitable to explicitly study the shape of the detected energy spectrum: Double Chooz [5], Daya Bay [21] and RENO [3]. Each of the experiments relies on the IBD reaction ( $\bar{\nu}_e + p \rightarrow e^+ + n$ ) as detection mechanism, in which electron antineutrinos interact with free protons in form of hydrogen nuclei. Calorimetric measurement of the energy  $E_{\text{visible}}$  deposited by the created positron allows to derive the kinetic energy of the incident antineutrino via  $E_\nu \approx E_{\text{visible}} + 0.8\text{ MeV}$ . In Table I the key parameters of the current three reactor neutrino experiments are given. Upcoming antineutrino

detectors placed at nuclear reactor cores are summarized in Table II. These experiments will search for light sterile neutrinos imprinting an unambiguous oscillation pattern in the measured event rate as a function of energy or baseline, or both. Global analyses including  $\nu_e$  and  $\bar{\nu}_e$  disappearance experiments at solar and accelerator detectors suggest  $|\Delta m_{\text{new}}^2| \approx 1.8 \text{ eV}^2$  and a mixing angle of  $\sin^2 2\theta_{\text{new}} \approx 0.09$  [16]. The size of the squared mass difference corresponds to an oscillation with  $L/E_\nu \approx 1 \text{ m/MeV}$ . The required experimental conditions are naturally given at research reactors: The core sizes are small enough to not smear the oscillation signature, and it is possible to build a detector only a few meters away from the core. Research reactors are in most cases loaded with HEU (Highly Enriched Uranium) fuel which simplifies the computation of the predicted flux and spectrum owing to the absence of burn-up effects. Hence, for a core operated with HEU, it is a good approximation that the produced antineutrinos are exclusively generated by  $\beta$ -instable  $^{235}\text{U}$  fission daughters. The small size of the sterile mixing angle requires detectors to possess systematics on the percent level as well as high statistics of the signal events. When it comes to the expected daily IBD rate the lower target mass or moderate reactor power – compared to the experiments of Table I – is compensated by the shorter detector to reactor distance. Regarding the energy resolution, however, most of these experiments are inferior to the km-baseline detectors. Because of shallow depths of the reactor buildings and thus the experimental sites, the cosmic background flux is barely reduced. Nevertheless, for most of these experiments the main source of background originates from the reactors themselves, in form of gamma radiation and neutrons.

For the analysis proposed in this article the Stereo project is used as example. Benefitting from the good energy resolution and signal-to-background ratio at the same time, it is currently under construction and data taking is planned for 2016. Located at a research reactor highly enriched in  $^{235}\text{U}$  at ILL Grenoble, France, it allows to measure the antineutrino spectrum generated by the fission products of  $^{235}\text{U}$ .

In contrast to this, the Double Chooz experiment observes an antineutrino flux where the number of fissions is shared among  $^{235}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{238}\text{U}$ , and  $^{241}\text{Pu}$  with average fission fractions of 0.49, 0.35, 0.09, and 0.07 [30]. Variations in the fission fractions  $\alpha$  are caused by reactor fuel burn-up. This opens the possibility to search for variations of spectral features linked to changes in the composition of fissioning actinides. Since reactors are partly refueled at different times, they have a complicated burn-up history. Experiments with multiple reactor cores are therefore not suited for this particular measurement, as their detectors measure the integrated flux of all reactors nearby. But the simple experimental configuration of Double Chooz with only

Table I. Near detector parameters of currently running  $\theta_{13}$ -experiments [2, 3, 5]. The target mass  $m_t$ , thermal power of the nuclear reactor  $P_{\text{th}}$  and the flux-weighted baseline  $L$  are given.  $R_{\text{IBD}}$  denotes the average IBD rate. The energy resolution  $\sigma_E/E$  is given at 1 MeV visible energy. For the case of Double Chooz the resolution was inferred from the far detector performance.

	Double Chooz	Daya Bay	RENO
$m_t$ [t]	8.3	$3 \times 20$	15
$P_{\text{th}}$ [GW]	8.5	$6 \times 2.9$	$6 \times 2.8$
$L$ [m]	400	500	409
$R_{\text{IBD}}$ [ $\text{day}^{-1}$ ]	300	1900	780
$\sigma_E/E$	0.08	0.08	0.07

two reactor cores allows reactor spectrum measurements at different average fission fractions. Moreover, the best case of a single reactor measurement is given during long phases with only one reactor running.

A LEU fueled core will emit an antineutrino spectrum

$$S_{\text{LEU}}(E_\nu) = \sum_k \alpha_k S_k(E_\nu), \quad (2)$$

where  $k = ^{235}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{238}\text{U}$  and  $^{241}\text{Pu}$ . The spectra  $S_k(E_\nu)$  in Eq. (2) are normalized to the number of antineutrinos created per fission by the  $k$ -th isotope. Then, the fission fraction  $\alpha_k$  reflects the portion of fissions provided by the actinide  $k$ .

As discussed above, the shoulder in the antineutrino spectra might be related to one specific actinide. The antineutrino spectra measured at reactors fueled with LEU or HEU provide the required information by means of their spectral shape. These spectra are e.g. measured by the Double Chooz near detector and the Stereo experiment. We will show the potential to test the following three hypotheses: the shoulder is created (1) with similar strength by all actinides, (2) solely by  $^{235}\text{U}$  or (3) by any actinide except  $^{235}\text{U}$ .

Based on the reference antineutrino spectra from Huber-Haag [15, 40], expected datasets for the Double Chooz near detector and the Stereo experiment can be computed. The  $\bar{\nu}_e$  spectrum observed by Double Chooz is computed using Eq. (2) assuming the fission fractions to be as quoted above. For Stereo the reactor neutrino spectrum is taken to correspond to a  $\bar{\nu}_e$  spectrum emitted by  $^{235}\text{U}$  solely. In order to introduce the shoulder artificially, a Gaussian shaped excess is added to the spectra. The width and integral of the Gaussian is obtained from the Double Chooz spectrum published in Ref. [5]. In our computation, the same percentage of detected IBD events in weight is given to the additional Gaussian of our Double Chooz prediction. The strength of the shoulder in the Stereo prediction is adjusted with respect to the above-mentioned three hypotheses.

Table II. Upcoming short baseline projects at nuclear reactors and their projected parameters. The IBD detection technique (PS: plastic scintillator, LS: liquid scintillator), the target mass  $m_t$ , thermal power of the nuclear reactor  $P_{th}$  and the reactor to detector baseline  $L$  are given.  $R_{IBD}$  denotes the expected IBD rate at reactor on and shortest baseline, S/B is the signal-to-background ratio. The photon statistical part of the energy resolution  $\sigma_{E,Ph}/E$  is given at 1 MeV visible energy. The reactor fuel is classified in Low Enriched Uranium (LEU), Highly Enriched Uranium (HEU) or the content of  $^{235}\text{U}$  is quoted in percent.

experiment [Ref.]	technology	$m_t$ [t]	$P_{th}$ [MW]	fuel	$L$ [m]	$R_{IBD}$ [ $\text{day}^{-1}$ ]	S/B	$\sigma_{E,Ph}/E$
CARR [31]	LS or D <sub>2</sub> O	-	60	20%	7+(11 or 14)	-	-	0.1-0.3
DANSS [32, 33]	PS	0.9	3000	LEU	9.7-12.2	$10^4$	100	0.18
NEOS [34]	Gd-LS	1	2800	LEU	25	1000	22	0.05
Neutrino-4 [35, 36]	Gd-LS	1.4	100	HEU	6-13	1800	$\sim 1$	-
Stereo [37]	Gd-LS	1.8	57	HEU	8.8-11.2	410	1.5	0.05
SoLi $\delta$ [38]	PS	2.9	60-80	HEU	6-8	1200	3	0.14
Prospect [39]	$^6\text{Li}$ /Gd-LS	1+10	85	HEU	(7-10.5)+(15-20)	-	1	0.045

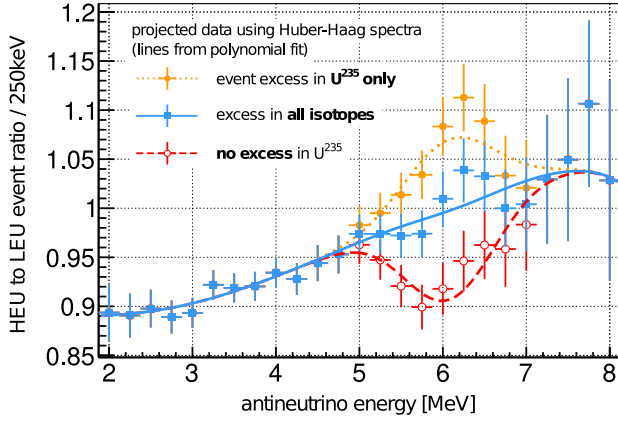


Figure 1. Event ratio of HEU to LEU antineutrino spectra for three hypotheses (see text). Data points show the event ratio of the projected data for Stereo (HEU) and Double Chooz near detector (LEU) using the Huber-Haag spectra for two years of data taking. The errors are statistical and include the model uncertainty of the Huber-Haag spectra taking into account correlations between the different isotopes. The detector response is not included in this plot. The lines are obtained from a polynomial fit to the Huber-Haag spectra.

In Fig. 1 the event ratio of the Double Chooz near detector and the Stereo prediction for two years of data taking is plotted. The blue solid line is the case where all four isotopes contribute to the event excess with the same strength and is similar to the ratio in absence of any spectral distortion. It is obtained by fits of 5-th order polynomial to the converted Huber-Haag spectra, for the Huber spectra the coefficients can be found in Ref. [15]. The slope of the ratio rises with energy, as  $^{239}\text{Pu}$ , which emits a softer  $\bar{\nu}_e$  spectrum, is only present in LEU fuel in a significant amount. If the shoulder in the spectra are produced only by a subset of actinides, a bump-shaped excess (orange dotted line) or reduction (red dashed line) shows up in the ratio. The statistical significance with the assumed two years of run time is  $5.9\sigma$  for the scenario of no bump in the  $^{235}\text{U}$  spectrum,

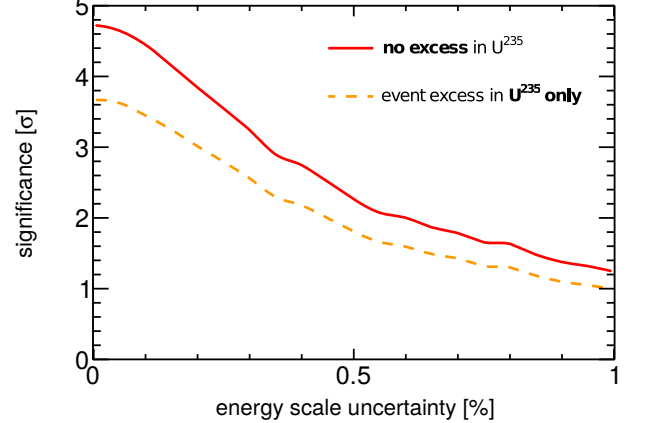


Figure 2. Significance as a function of the energy scale uncertainty.

which would imply the excess is only seen in Double Chooz but not in Stereo. Slightly less significant ( $4.6\sigma$ ) would be the case with an event excess in  $^{235}\text{U}$  only. The systematics of the conversion spectra and their correlations are taken into account for both scenarios. If we include the energy resolution of the detectors the significance of the effect weakens. With about 8% energy resolution in Double Chooz at 1 MeV energy and assuming  $\sim 12\%$  for Stereo at 3 MeV we still obtain a significance of  $4.9\sigma$  ( $3.7\sigma$ ) for the case of no excess in  $^{235}\text{U}$  (excess in  $^{235}\text{U}$  only). Here we assume the energy resolution scales just with the statistics of the collected photo electrons. However, for the case of Stereo this is a conservative assumption, since at low energies the resolution is dominated by systematic effects, which are suppressed at higher energies [37]. For the final significance also the contributions of backgrounds and the precision of the energy scale need to be included. In particular the latter has a strong impact on the result. Therefore, sophisticated and accurate detector calibration also at higher energies above 5 MeV is crucial. In Figure 2 the dependence of the significance on the

absolute knowledge of the energy scale is shown. Here we assume the energy scale uncertainty to be the same in both detectors. For different energy scale uncertainties the significance will be strongly limited by the detector with the larger error. The precision on the energy scale in the recent  $\theta_{13}$ -experiments Double Chooz, RENO and Daya Bay is already in the sub per cent regime [5, 41, 42] and might further improve in the future. Whether a similar precision can be reached in a smaller Stereo type detector needs to be demonstrated. Since such a precision might be out of reach in Stereo one could constrain the energy scale systematics using the 2-5 MeV range when comparing the experiments to improve the sensitivity.

Our study shows in summary that the comparison of the measured reactor antineutrino spectrum in the Double Chooz and Stereo experiments is a powerful tool to study the origin of the observed shape distortion compared to flux predictions. After two years of data taking sufficient statistics is collected allowing to distinguish different scanrios as no event excess in the 5-7 MeV region in  $^{235}\text{U}$  or a distortion exclusively in the  $^{235}\text{U}$  spectrum at the  $5\sigma$  level, neglecting detection systematics. The main challenge will be to control the precision of the energy scale in the neutrino detectors to the few per mille level in both experiments.

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